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RESEARCH MEMORANDUM

AN ACCELERATION SCHEDULE CONTROL FOR ACCELERATING A TURBOJET ENGINE AND ITS USE WITH A SPEED CONTROL

By Theodore F. Gerus, Albert G. Powers and Herbert J. Heppler

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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RESEARCH MEMORANDUM

AN ACCELERATION SCHEDULE CONTROL FOR ACCELERATING A TURBOJET ENGINE AND ITS USE WITH A SPEED CONTROL

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SUMMARY

An acceleration-limiting control was used on a turbojet engine in order to study the feasibility of its use as an acceleration control. A proportional-plus-integral type of controller was used in this investigation. Transient response data were obtained to investigate the control-system response and stability. The response was evaluated in terms of schedule overshoot and acceleration time as a function of control-parameter settings and input disturbance rate.

Both schedule overshoot and acceleration time were found to be a function of rate of input disturbance, schedule level, system gain, and controller time constant. All these parameters, therefore, must be adjusted to provide a compromise between fast acceleration and small overshoot. When the acceleration-limiting control was added to a proportional-plus-integral speed - fuel-flow control, a two-loop control resulted. Both control loops must be adjusted to provide a compromise between good acceleration characteristics and steady-state performance of the speed control. If the engine should go into stall or surge during an acceleration transient, both the one-loop and two-loop controls would add rather than subtract fuel flow and drive the engine further into undesirable regions. Therefore, this system would not be safe without an overriding control. However, the use of an acceleration-limiting schedule has an advantage over other limit schedules in that there is less dependence upon steady-state operating lines.

INTRODUCTION

Acceleration-limiting controls of the type considered in this report automatically limit engine parameters such as fuel flow, compressor discharge pressure, temperature, or acceleration according to a predetermined schedule. Investigations of temperature-limited acceleration controls have been presented in references 1 and 2. However, limiting fuel flow, compressor discharge pressure, or temperature has a distinct disadvantage in that the setting of the schedule limit depends on the steady-state operating line. Any deviation from this line caused by engine deterioration, production deviations, or sensor errors could offset the schedule limit. The use of acceleration as a schedule limit would minimize this disadvantage in that steady-state acceleration is always zero.

An investigation of an acceleration-limiting schedule control using a constant acceleration limit has been presented in reference 3. Since the stall and surge accelerations are a function of speed, however, a constant-acceleration limit cannot give optimum performance. Therefore, 4811
an experimental program was conducted with acceleration limit scheduled as a function of speed. This schedule was shaped to skirt the stall and surge region. A study of the margin necessary between the acceleration-limit schedule and stall and surge accelerations was made for several influencing factors such as input disturbance rate and control variations. In order to test the practicality of the accelerating control, a speed - fuel-flow control was added to study the operation of the combined system.

CONTROL SYSTEMS

Acceleration-Limiting Control

A block diagram of the acceleration-limiting control is shown in figure 1(a). The demand signal sets the fuel-flow rate for either transient or steady-state operation. During an acceleration transient, the demand simulates a signal from the operator to accelerate. Signals proportional to speed and acceleration are obtained through the use of the speed and acceleration sensor circuits. The speed signal is applied to the function generator unit to provide the acceleration-limiting schedule. The acceleration signal is compared with the scheduled acceleration signal, and the resulting error serves as an input to the acceleration controller. The action of the controller is a proportional-plus-integral type to produce a desired fuel-flow correction. However, the proportional-plus-integral control is in parallel with a low gain proportional circuit (fig. 1(b)), and thus the output is limited to negative values. The operation of this circuit can be explained with the following equations (symbols are defined in the Appendix).

When $V_o < 0$, the diode does not conduct, and

$$V_o(s) = - P_1 \frac{R_2}{R_1} \left(1 + \frac{1}{R_2 Cs}\right) V_i(s)$$

When $V_o > 0$, the diode conducts, and

$$V_o(s) = - P_1 \left(\frac{R_3}{R_1}\right) \frac{(1 + R_2Cs)}{1 + (R_2 + R_3)Cs} V_i(s)$$

Since R_3 is much less than R_2 or R_1, the positive output is negligible.

Acceleration-Limiting-Plus-Speed - Fuel-Flow Control

A block diagram of the speed control and acceleration-limiting control is shown in figure 2(a). The action of the acceleration loop in the two-loop control is exactly the same as in the acceleration-limiting control. The demand on the combined system is made in the form of a speed demand, however, rather than a fuel-flow demand. In the speed control, engine speed is sensed, and the speed signal is compared with a demand speed signal. The speed error signal is operated on by a proportional-plus-integral control that governs the demand fuel flow. When the speed error gets larger than a preset value, the gain of the control is decreased to stabilize the two-loop system. A schematic diagram of the stabilizing unit used for this purpose is shown in figure 2(b). The operation of this nonlinear element can be explained as follows:

When $V_o' < P_3E$, the diode does not conduct, and

$$V_o' = - \frac{R_2'}{R_1'} V_i'$$

When $V_o' > P_3E$, the diode conducts, and

$$V_o' = \frac{P_3E}{1 + \frac{R_3'}{R_2'}} - \frac{\frac{R_2'}{R_1'}}{1 + \frac{R_2'}{R_3'}} V_i'$$

Since $R_2' > R_3'$, there is a large decrease in gain when $V_o' > P_3E$.

COMPONENT DYNAMICS

Sensors

Engine speed. - A voltage proportional to speed was obtained by electronic conversion of pulses obtained from a magnetic pickup installed in the compressor housing opposite a row of compressor blades. The pick-up and electronic circuit had no measurable dynamics in the range of interest.

Engine acceleration. - A voltage proportional to acceleration was obtained by electronically differentiating the speed sensor output. However, differentiation amplifies noise components proportionally with frequency. Therefore, a high frequency filter in the form of $\frac{1}{(1 + \tau_F s)^2}$ was added in which τ_F was set at 0.03 second. 4811

Engine tailpipe temperature. - A system of thermocouples was spaced in the tailpipe to give a signal proportional to an average temperature. The system responded with an approximate first-order lag with a time constant that varied with speed from 0.63 to 0.33 second.

A thermocouple compensator of a lead-lag-lag nature was used to provide a signal response flat to 16 cycles per second at an engine speed of 4250 rpm and an overcompensated response at higher speeds. A more complete description is given in reference 2.

Fuel System

Fuel was fed to the engine manifolds through a differential-reducing-valve type of flow regulator that maintains a constant pressure drop across a throttle. The response of this valve system was flat to 100 cycles per second. The throttle area was varied by an electro-hydraulic servomotor. The response of this unit to an input voltage was essentially flat to 20 cycles per second. The control system thus varied the fuel flow by varying the voltage impressed upon the electro-hydraulic servomotor. A signal proportional to the throttle area was calibrated and used for transient fuel-flow measurements. (A complete description of this system is given in ref. 4.)

Engine Dynamics

Speed and acceleration - fuel-flow response. - The frequency response of engine speed and acceleration to fuel flow as approximated from experimental data is shown in figure 3. The frequency response represents engine dynamics at 4500 rpm. The transfer function which approximately fits the speed - fuel-flow response is given by

$$\frac{K_N e^{-t_d s}}{(1 + \tau_{L,1}s)(1 + \tau_{L,2}s)}$$

Because acceleration transient times are relatively short, about 5 seconds for the complete transient, the ability of a system to follow an accelerating schedule depends upon the higher frequency characteristics of acceleration - fuel-flow response. The lowest pertinent frequencies are about $\frac{1}{2}$ cycle during the transient; thus engine acceleration - fuel-flow response below about 0.1 cps need not be considered. Therefore, the dynamics of engine acceleration fuel flow may be approximated as

$$\frac{K_{\dot{N}} e^{-t_d s}}{(1 + \tau_{L,2}s)}$$

Variation of steady-state speed with fuel flow is given in figure 4. The steady-state speed - fuel-flow gain (K_N) can be derived from this curve. As shown in figure 5, the total variation of this gain with speed is in the ratio of more than 8, the highest gain being at idle.

The midfrequency acceleration - fuel-flow gain ($K_{\dot{N}}$) variation with speed is shown in figure 6. It can be shown that

$$K_{\dot{N}} = \frac{K_N \tau_D}{\tau_{L,1}}$$

The total variation of this gain is in the ratio of about 1.5, which is much less than the speed - fuel-flow gain.

The dead time varies with speed as shown in figure 7. The dead time was found to be on the order of 0.10 second at idle, dropping down to about 0.052 second at 6500 rpm, and rising again to about 0.078 second at rated speed.

The two-engine lag-time constants, $\tau_{L,1}$ and $\tau_{L,2}$, are shown in figure 8 as a function of engine speed. The first time constant ($\tau_{L,1}$) varies between 9 and 0.9 second; the second time constant is much shorter, varying between 0.08 and 0.032 second.

Surge and stall limits. - Data were taken to determine the engine acceleration and speed when the engine first went into stall or surge after a large disturbance in fuel flow. Figure 9 shows a number of these data points. The shape and the operating range of the schedule used are shown in relation to these points.

PROCEDURE AND RANGE OF VARIABLES

The experimental program consisted of engine acceleration controlled by (1) the acceleration-limiting control (one-loop control) and 4811
(2) the combination acceleration-limiting and speed-error control (two-loop control).

Transient data were recorded on a direct-reading oscillograph, whose frequency response was essentially flat to at least 25 cycles per second on all channels.

One-Loop Control

A ramp disturbance in fuel flow was used as a demand signal to determine the performance of the acceleration-limiting control. The transients were initiated at an engine speed of 4000 rpm (idle), and the following parameters were varied individually: (1) ramp rate of disturbance; (2) schedule-level bias; (3) controller gain; and (4) controller time constant. The ramp rate of disturbance was varied between 412 and 4125 pounds per hour per second and was held constant at 2062 pounds per hour per second when other parameters were varied. Figure 9 shows the range of schedule levels used.

Evaluation of the control system and its parameters was made from the following criteria:

(1) Stability-limits

(2) Overshoot of preset schedule (hereafter called schedule overshoot)

(3) Acceleration time from 4000 to 5500 rpm and 4000 to 6500 rpm

Two-Loop Control

In order to have the two-loop control accelerate the engine rapidly and safely and also provide acceptable steady-state speed control throughout the range of engine speeds used, each controller gain and time constant must be properly set. Controller time constants of 3 seconds for the speed loop and 0.20 second for the acceleration loop were chosen on the basis of single-loop preliminary data. When the two loops are combined, only certain combinations of gains will produce stable operation. Generally, for high gain in one loop, low gain is required in the other for stability reasons. The theoretical plot of the stability limit gains is shown in figure 10.

When small speed errors exist, the fuel flow demanded by the speed controller does not produce accelerations high enough to cross the schedule so only the speed control is in operation. For this range of speed errors, the speed control gain was set as shown in figure 10 at point A. When the speed error exceeds a preset amount, the nonlinear circuit in the speed control decreases the speed control gain. For large speed errors the fuel flow demanded by the speed control is great enough to produce accelerations greater than the scheduled amount, which will bring the acceleration loop into the control. Thus the gain of the speed loop has been set to a new value, the acceleration loop has come into the control, and a new operating point (B) on figure 10 has been set. In order to find the effects of each loop gain when the two loops are operating, each loop gain was decreased holding the other gain constant.

Figure 11 shows the relative open-loop gain plotted against frequency of each control loop when the system is set at operating point B of figure 10. These open-loop responses were used in the calculations for figure 10. Included in the acceleration-control amplitude response are the dynamics of the engine (at 4500 rpm), fuel system, speed sensor, acceleration sensor, and its proportional-plus-integral control. Included in the speed-control amplitude response are the dynamics of the engine (at 4500 rpm), fuel system, speed sensor, and its proportional-plus-integral control. When the control settings are made as shown in figure 10, the acceleration control has higher gain at frequencies higher than 0.0052 cycles per second, but the speed control gain is higher below this frequency. This is a basic requirement for the control system to operate since it is necessary that the acceleration control have more effect than the speed control during short, rapid acceleration transients.

RESULTS AND DISCUSSION

One-Loop Control

A typical acceleration transient is shown in figure 12. Recorded traces are speed, fuel flow, tailpipe temperature, controller output, and acceleration. Superimposed upon the acceleration trace is the acceleration schedule. From steady-state operation at 4000 rpm a fuel-flow disturbance of 2062 pounds per hour per second is applied until nearly rated fuel flow is reached. The fuel flow increases as a ramp for approximately 0.8 second until the acceleration schedule is reached. When

the acceleration exceeds the schedule, the controller output calls for a reduction in fuel flow. However, the acceleration must continue to rise from the time it first reaches the schedule until the end of the dead time (t_d), which produces an irreducible overshoot (about 50 percent of the experimental overshoot obtained in this case). The acceleration then responds to the fuel-flow signal t_d earlier in time. Because of the filter in the acceleration sensor, this response is somewhat sluggish 4811
during the initial overshoot. After the initial overshoot, the controller tracks the schedule very well until the acceleration demanded by the fuel flow is less than the schedule.

Stability limits. - Figure 13 shows typical transient data for the control system when it becomes unstable during a portion of the transient. The system was considered unstable if two cycles of oscillation appeared. The frequency of this instability is about 2.4 cps, very close to the calculated value. Experimental- and theoretical-system stability limits are shown in figure 14 for accelerations in which the controller gain and time constant were varied. The theoretical stability limit is based upon engine dynamics at 5000 rpm. Of the engine dynamics, the major factor of stability is the dead time. For very long time constants the gain approaches 0.0725. This represents a loop gain of 2.02 in the midfrequency region. Making the time constant of the controller small enough to approach $\tau_{L,2}$ decreases the maximum allowable proportional gain. However, decreasing the controller time constant also increases the range of the integrator action. Therefore, within this range the response will be improved.

Overshoot and acceleration time. - Schedule overshoot and acceleration time are plotted against controller gain and time constant in figure 15. Acceleration time was measured between 4000 and 5500 rpm, and 4000 and 6500 rpm. As the gain at each controller-time-constant setting is increased to the stability limit, the overshoot is decreased. The acceleration time is increased as the gain is increased but this is not a penalty because the object of the control is to limit acceleration, which in itself will fix a minimum theoretical acceleration time as shown in figure 15. The overshoot is minimized as the controller time constant approaches $\tau_{L,2}$ and the gain approaches the stability limit.

Figure 16 illustrates the effects of ramp rate of disturbance on schedule overshoot and acceleration time. The schedule overshoot increases nearly linearly with ramp rates over the entire range of ramp rates used. A large part of the change in overshoot is due to dead time since the irreducible overshoot caused by dead time is a function of rate of change of acceleration. When the transient starts at 5000 rpm rather than 4000 rpm, the dead time is 35 percent less, and thus the overshoot is less. The acceleration time decreases as the ramp rate is increased because of less time to reach the schedule and higher accelerations during the schedule overshoot.

Figure 17 shows the effects of schedule level on acceleration time and schedule overshoot. As expected, acceleration time decreases when the schedule is raised. However, as the capacity for acceleration of the engine is approached, the acceleration approaches a constant value. The constant value approached by the acceleration-schedule control is very nearly that approached by the temperature-schedule control in reference 2. The schedule overshoot remains approximately the same with variation of schedule level until the schedule reaches the more nonlinear regions of the engine.

A very high schedule level produces fast accelerations but may also result in stall or surge as shown in figure 18. After going into stall or surge, acceleration will decrease and may even go below the schedule level. If this occurs, the controller will increase the fuel flow and drive the engine further into the undesirable region until the fuel-flow limit is reached. The resulting damage to the engine would depend on the fuel-flow demand being made.

Two-Loop Control

A typical transient in acceleration using the two-loop control is shown in figure 19. Recorded traces are speed, fuel flow, tailpipe temperature, acceleration-controller output, speed-controller output, and acceleration. Superimposed upon the acceleration trace is the acceleration schedule. A ramp disturbance in speed demand is made upon the system. This demand is compared with measured speed, and the resulting error is operated on by a proportional-plus-integral control. The output of this control sets a desired fuel flow to the engine. When the speed error reaches a preset value, the gain of the control is decreased. When the acceleration crosses the schedule, the acceleration control acts the same as it did alone. After the initial overshoot, the system tracks the schedule very well.

Figure 20 shows the effects of each loop gain of the system on schedule overshoot and acceleration time. (The gains of both loops were at operating point B on figure 10 at zero-db reference gain.) A decrease in speed-controller gain decreases overshoot. A decrease in acceleration-controller gain increases overshoot by about the same amount. Thus we have two controls, each seeking to comply with opposite demands. Variation in acceleration-controller gain does not appreciably affect acceleration time in this range. However, by decreasing the speed-controller gain, the acceleration time increases.

If the engine should go into stall or surge when using the two-loop control, considerable damage could result. Since acceleration would decrease, the acceleration-limiting control loop would have little or no effect in decreasing fuel flow. The speed control would demand a fuel-flow increase as a function of the integrated speed error.

SUMMARY OF RESULTS

An acceleration-limiting control was used on a turbojet engine to study its performance as an acceleration control. The following results were obtained:

When using the acceleration-limiting controller alone, midfrequency open-loop gain is limited to a maximum of 2.02 (at 5000 rpm) for a stable proportional control. The major part of the phase shift that causes instability is due to dead time. 4811

After the initial schedule overshoot (minimum of about 175 rpm/sec), the control tracked the schedule very well. A compromise between schedule overshoot and acceleration time is required for all settings of controller gain and time constant, demand rate, and schedule level.

As the schedule is raised, the acceleration time decreases and finally approaches a limit. This limit is very close to the limit approached by the temperature-schedule control used in reference 2.

The acceleration-limiting control has an undesirable feature in that if stall or surge are encountered, acceleration decreases and the control adds fuel flow to drive the engine further into undesirable conditions.

When the acceleration loop is added to a speed - fuel-flow control loop, the parameters of each control must be adjusted to provide a compromise between good acceleration characteristics and steady-state speed control. A nonlinear gain must be provided in the speed control loop in order to attain this performance and yet remain stable.

If stall or surge are encountered with the two-loop control, both controls will act to drive the engine into the undesirable conditions.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, February 21, 1958

APPENDIX - SYMBOLS

C	capacitor component
E	battery voltage
K_N	steady-state speed - fuel-flow gain
$K_{\dot{N}}$	midfrequency acceleration - fuel-flow gain
P	potentiometer setting
R	resistive component
s	Laplacian operator
τ_D	differentiator time constant
τ_L	speed - fuel-flow, lag-time constant
τ_F	filter time constant
t_d	speed - fuel-flow dead time
V	amplifier voltage

Subscripts:

i	input
o	output
1,2,3	designation of resistor, capacitor, or lag-time constant as noted in diagrams

Superscript:

$'$	nonlinear stabilizing unit

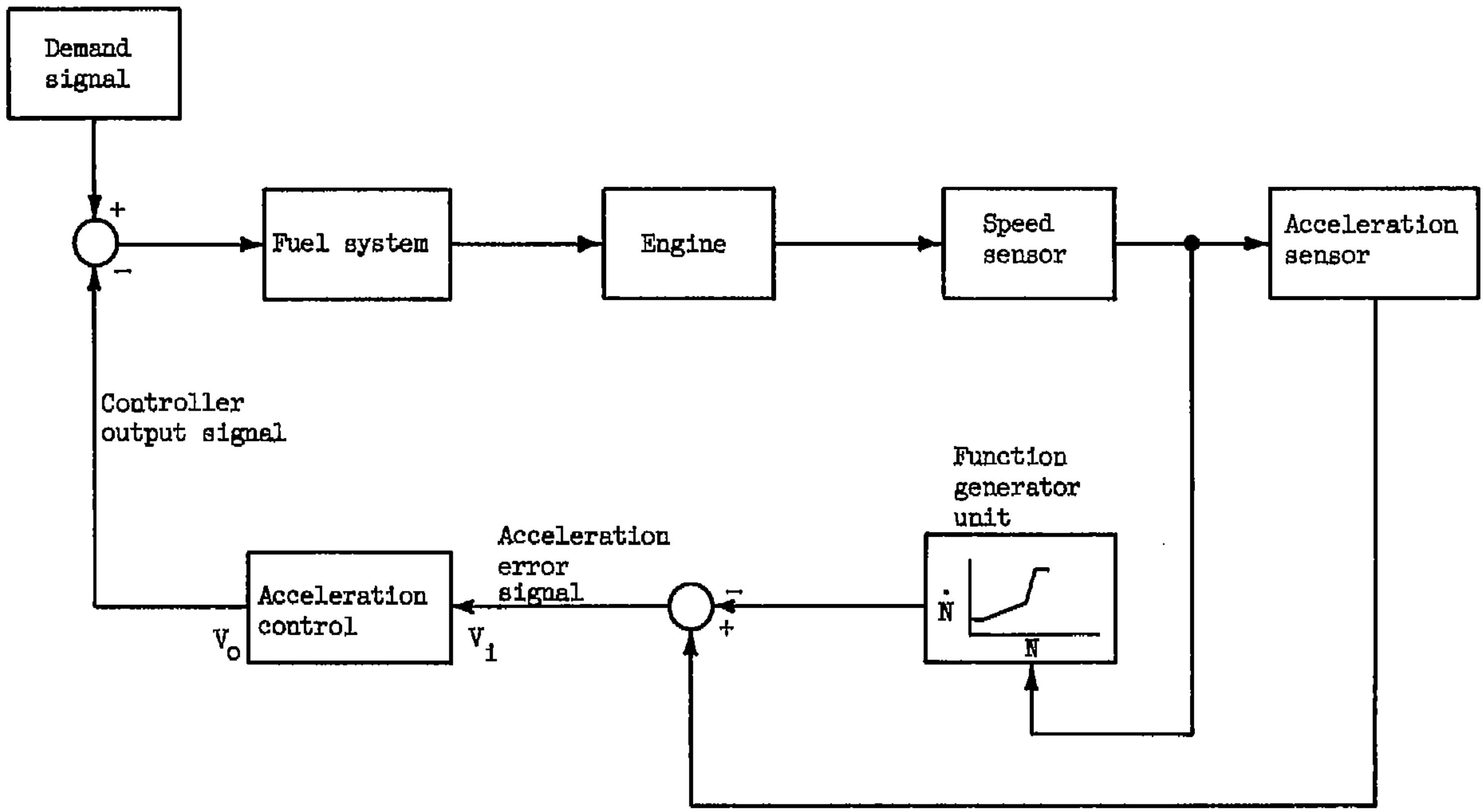
REFERENCES

1. Heppler, Herbert, Stiglic, Paul M., and Novik, David: Analytical and Experimental Investigation of a Temperature-Schedule Acceleration Control for a Turbojet Engine. NACA RM E56C08, 1956.

2. Gerus, Theodore F., Powers, Albert G., and Heppler, Herbert J.: A Temperature-Schedule Acceleration Control for a Turbojet Engine 4811
and Its Use with a Speed Control. NACA RM E57I18a, 1957.

3. Stiglic, Paul M., Heppler, Herbert, and Novik, David: Experimental and Analytical Investigation of an Acceleration Regulating Control for a Turbojet Engine. NACA RM E56C07, 1956.

4. Otto, Edward W., Gold, Harold, and Hiller, Kirby W.: Design and Performance of Throttle-Type Fuel Controls for Engine Dynamics Studies. NACA TN 3445, 1955.



(a) Block diagram of acceleration-limiting control.

Figure 1. - Control loop for acceleration-schedule acceleration control.

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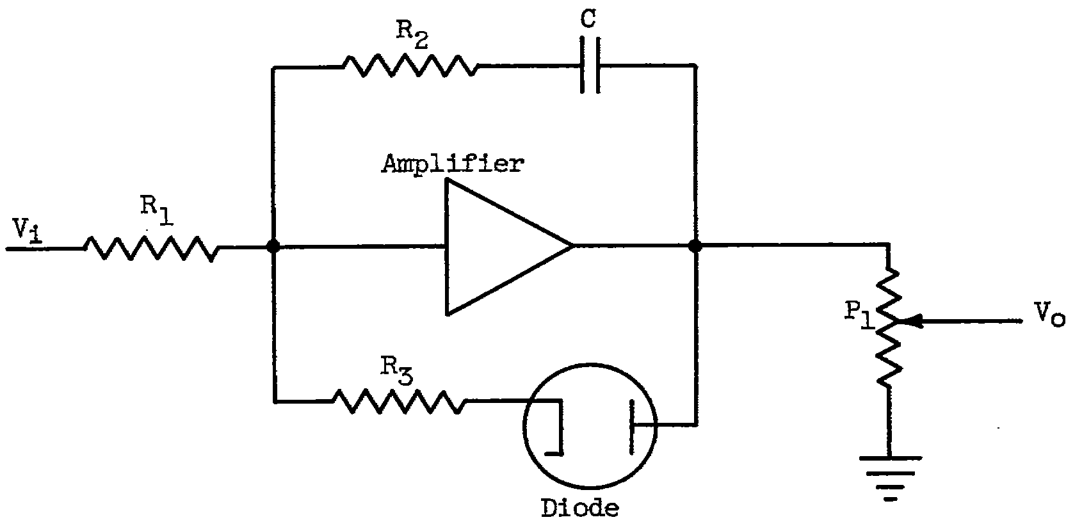
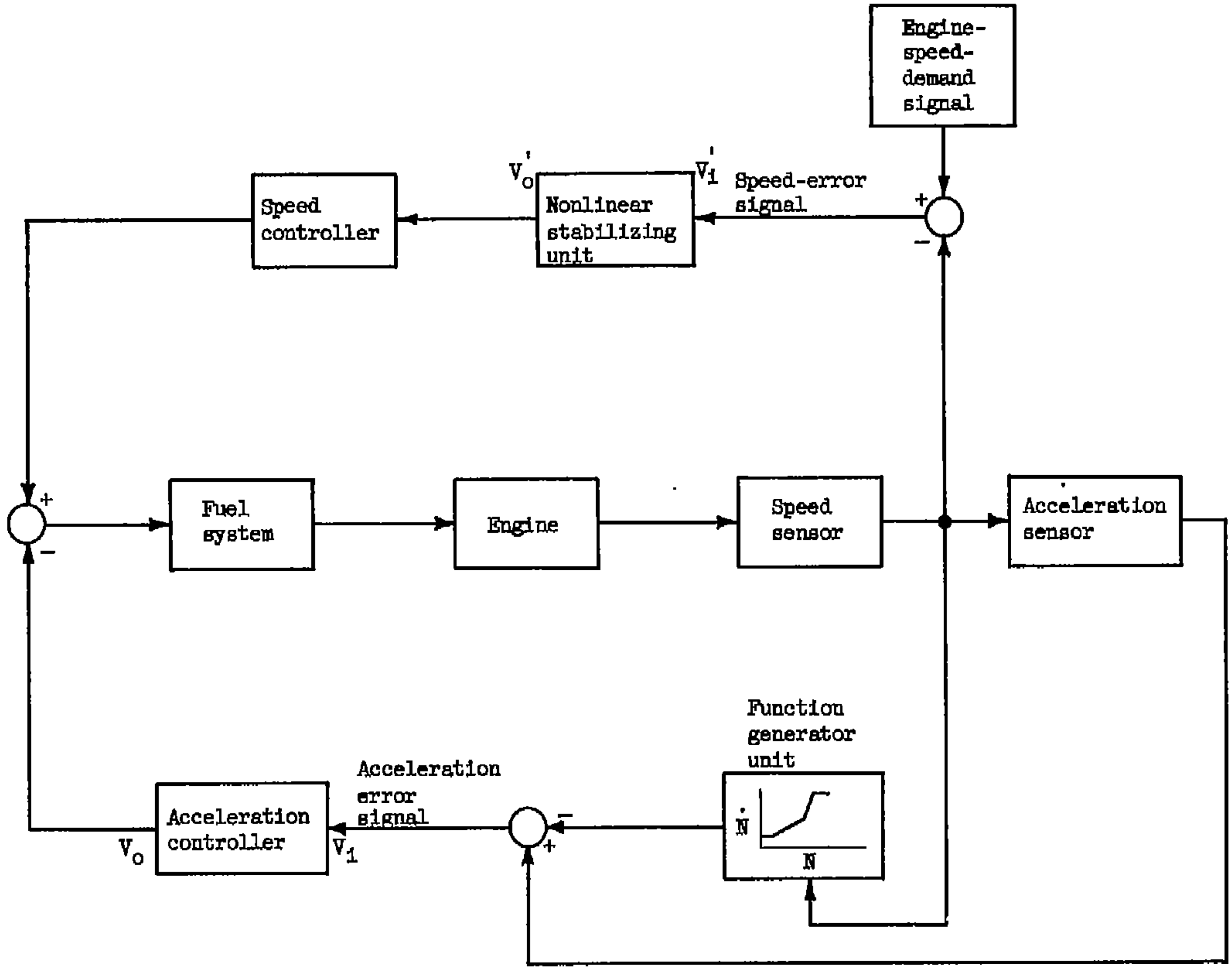


(b) Schematic diagram of nonlinear control.

Figure 1. - Concluded. Control loop for acceleration-schedule acceleration control.



(a) Block diagram.

Figure 2. - Control loops for acceleration-schedule acceleration control and speed control.

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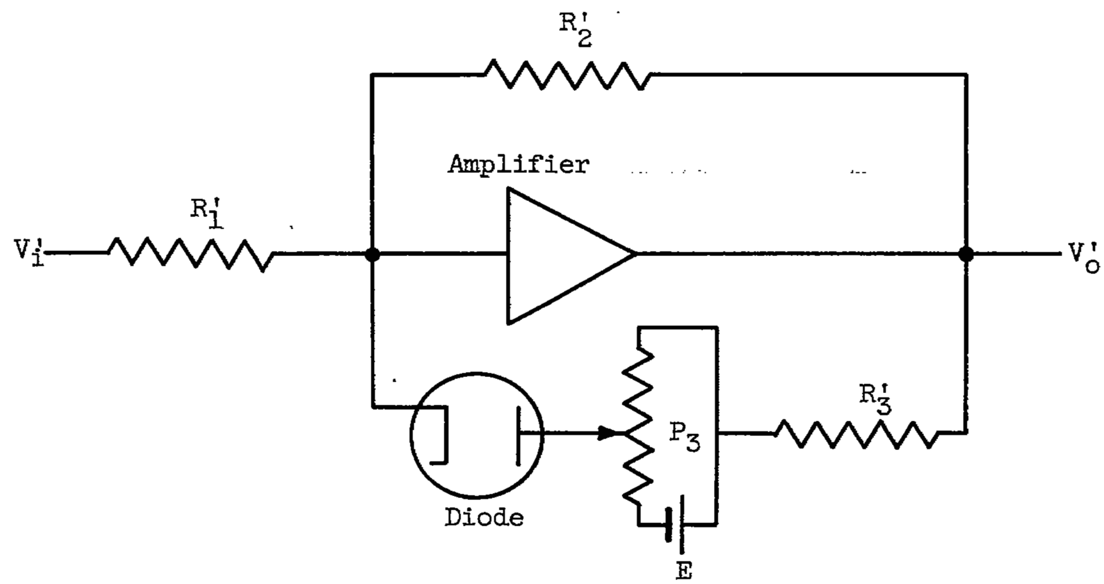
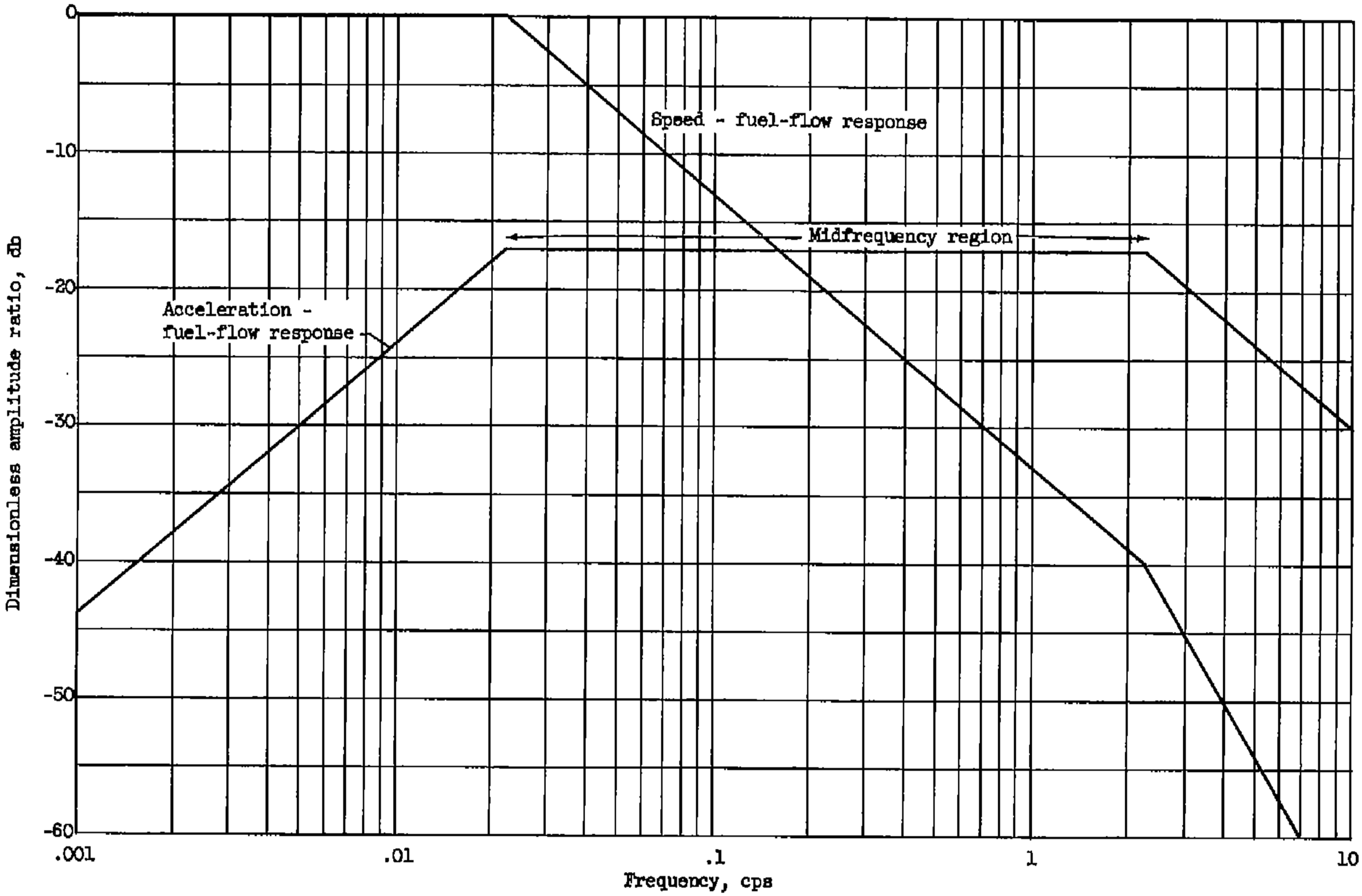


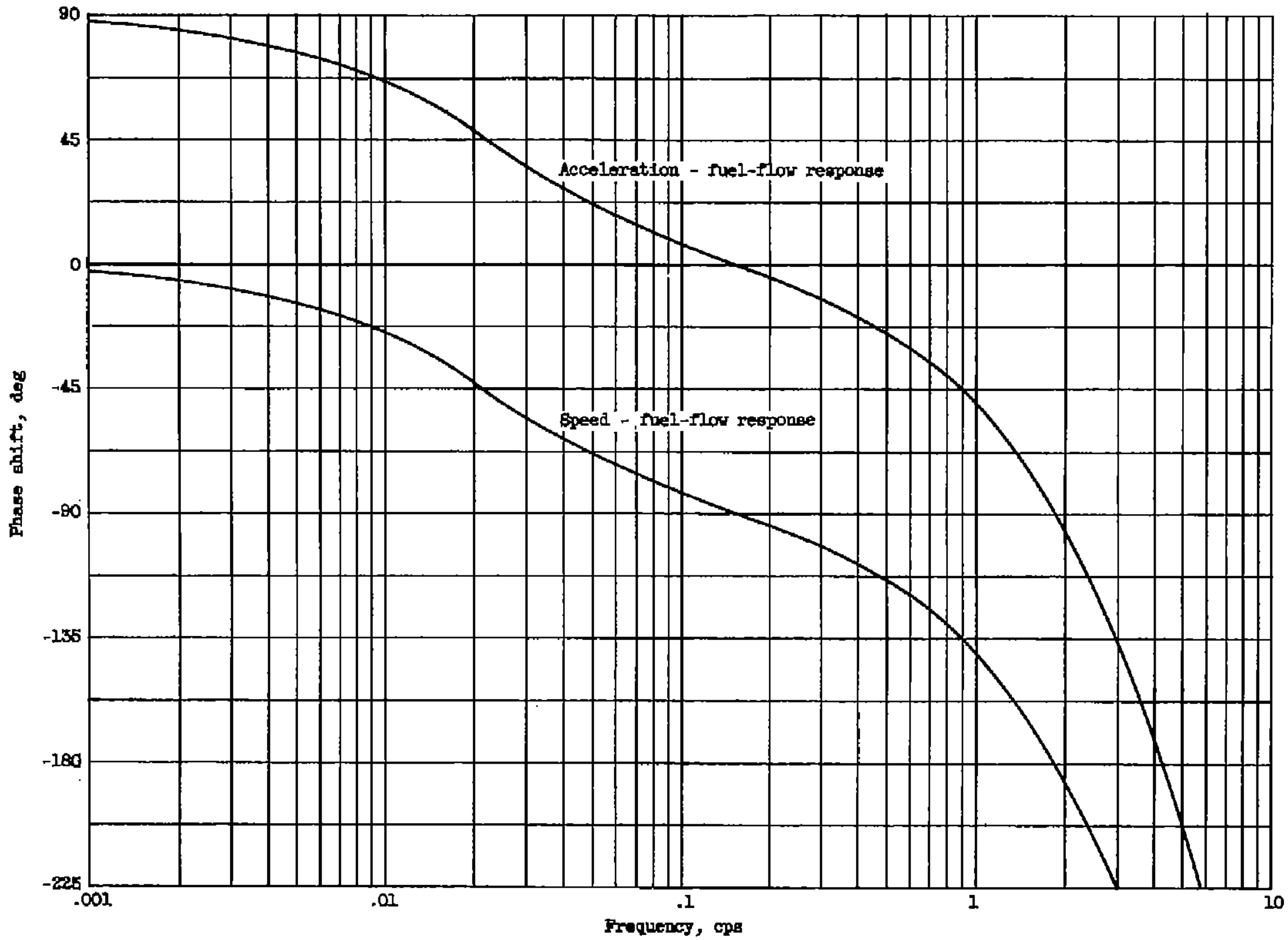
(b) Schematic diagram of nonlinear stabilizing unit.

Figure 2. - Concluded. Control loops for acceleration-schedule acceleration control and speed control.



(a) Amplitude frequency.

Figure 3. - Frequency response of engine speed and acceleration fuel flow at 4500 rpm.



(b) Phase shift frequency.

Figure 3. - Concluded. Frequency response of engine speed and acceleration fuel flow at 4500 rpm.

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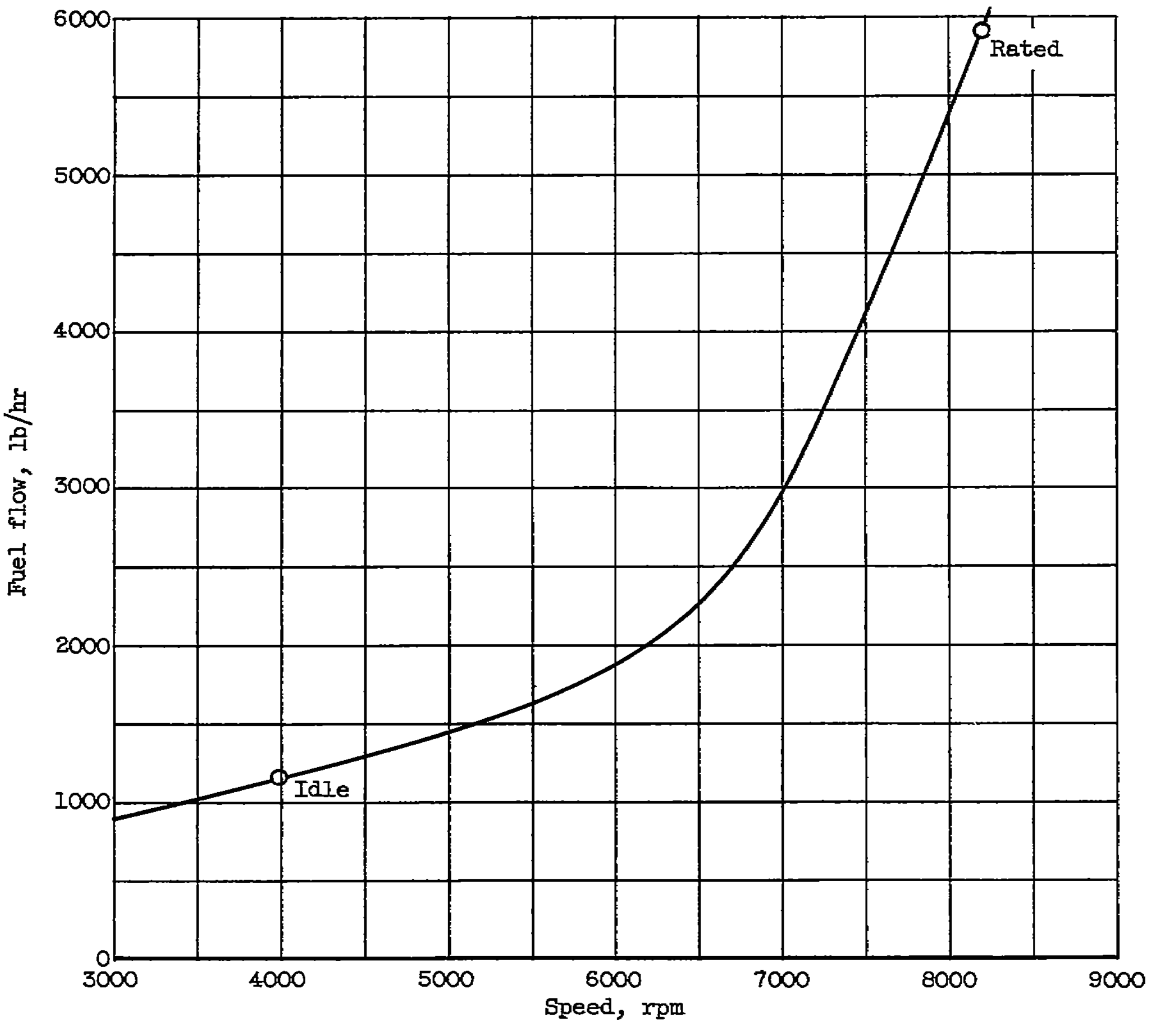

Figure 4. - Variation of steady-state fuel flow with speed.

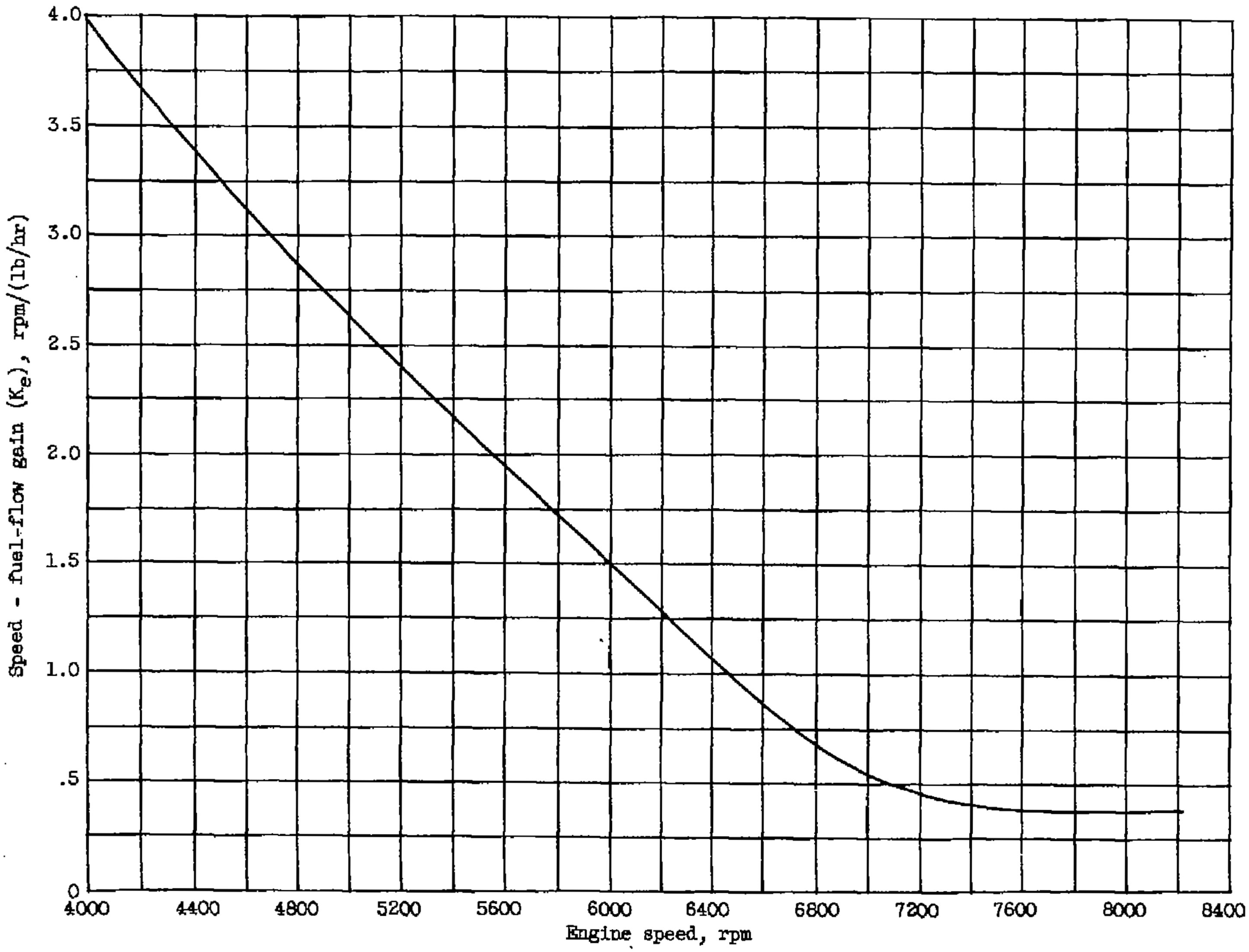

Figure 5. - Variation of steady-state speed - fuel-flow gain with speed.

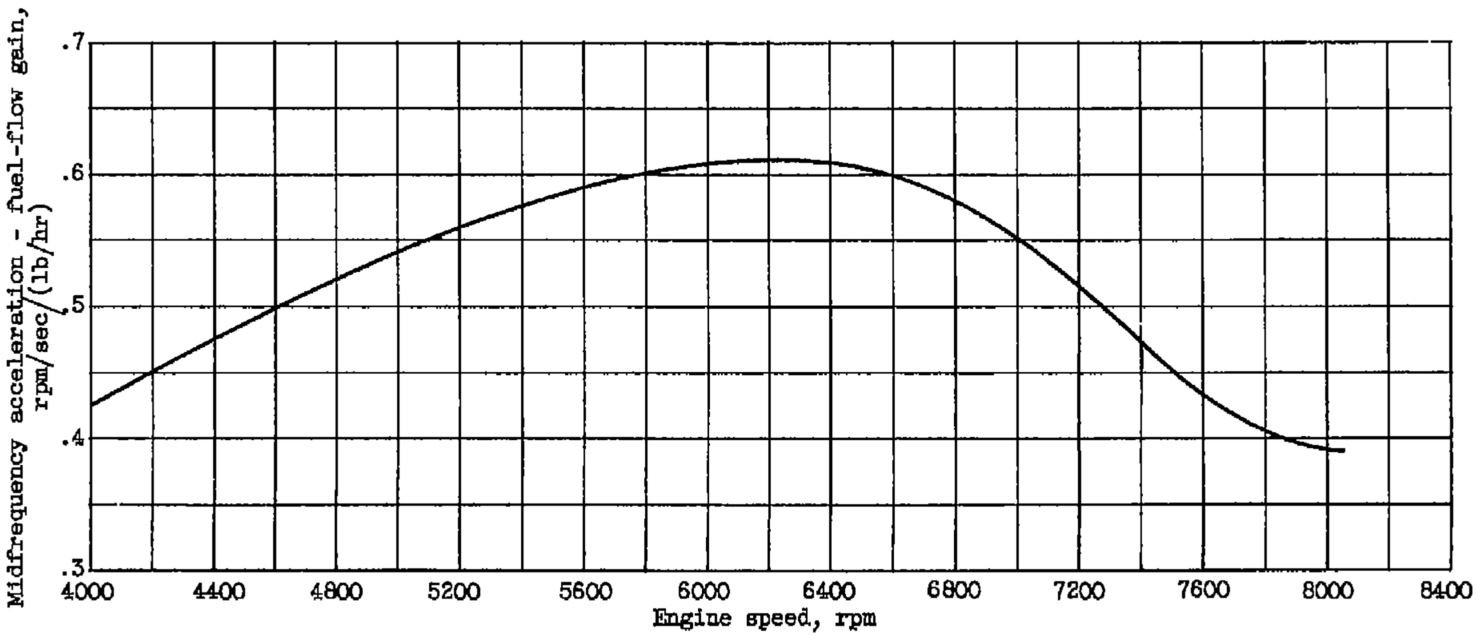

Figure 6. - Variation of midfrequency acceleration - fuel-flow gain with speed.

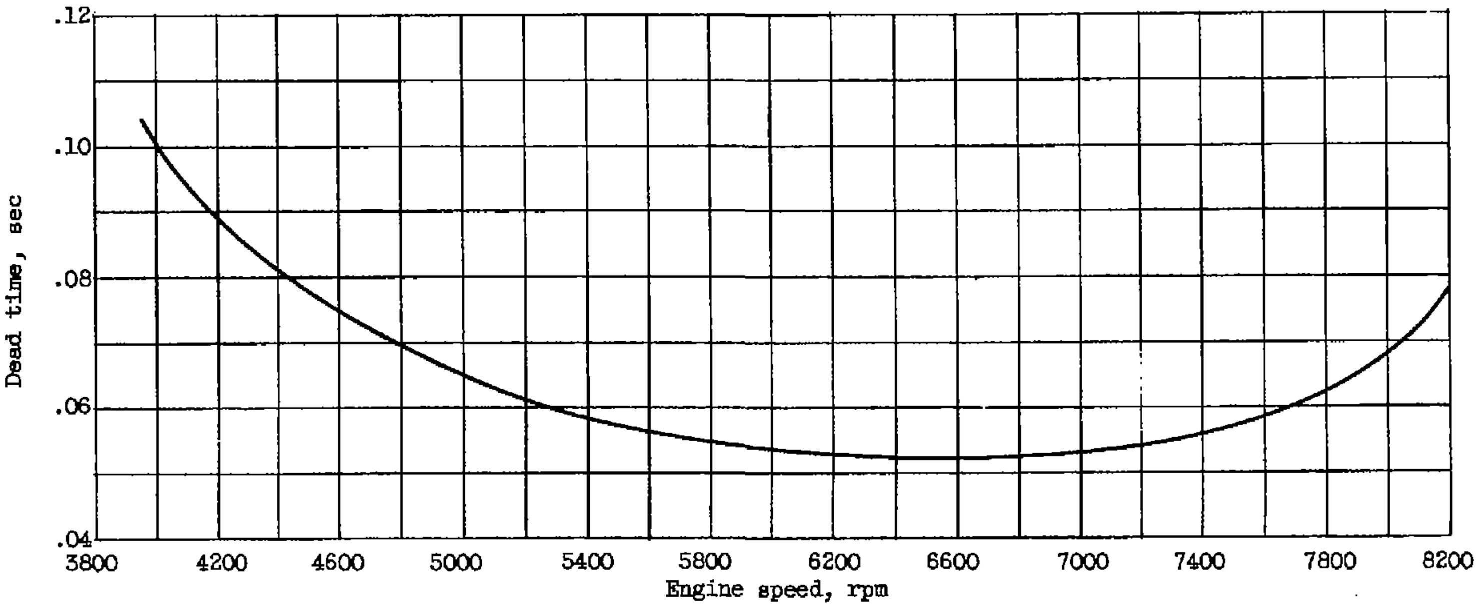

Figure 7. - Variation of speed and acceleration - fuel-flow dead time with speed.

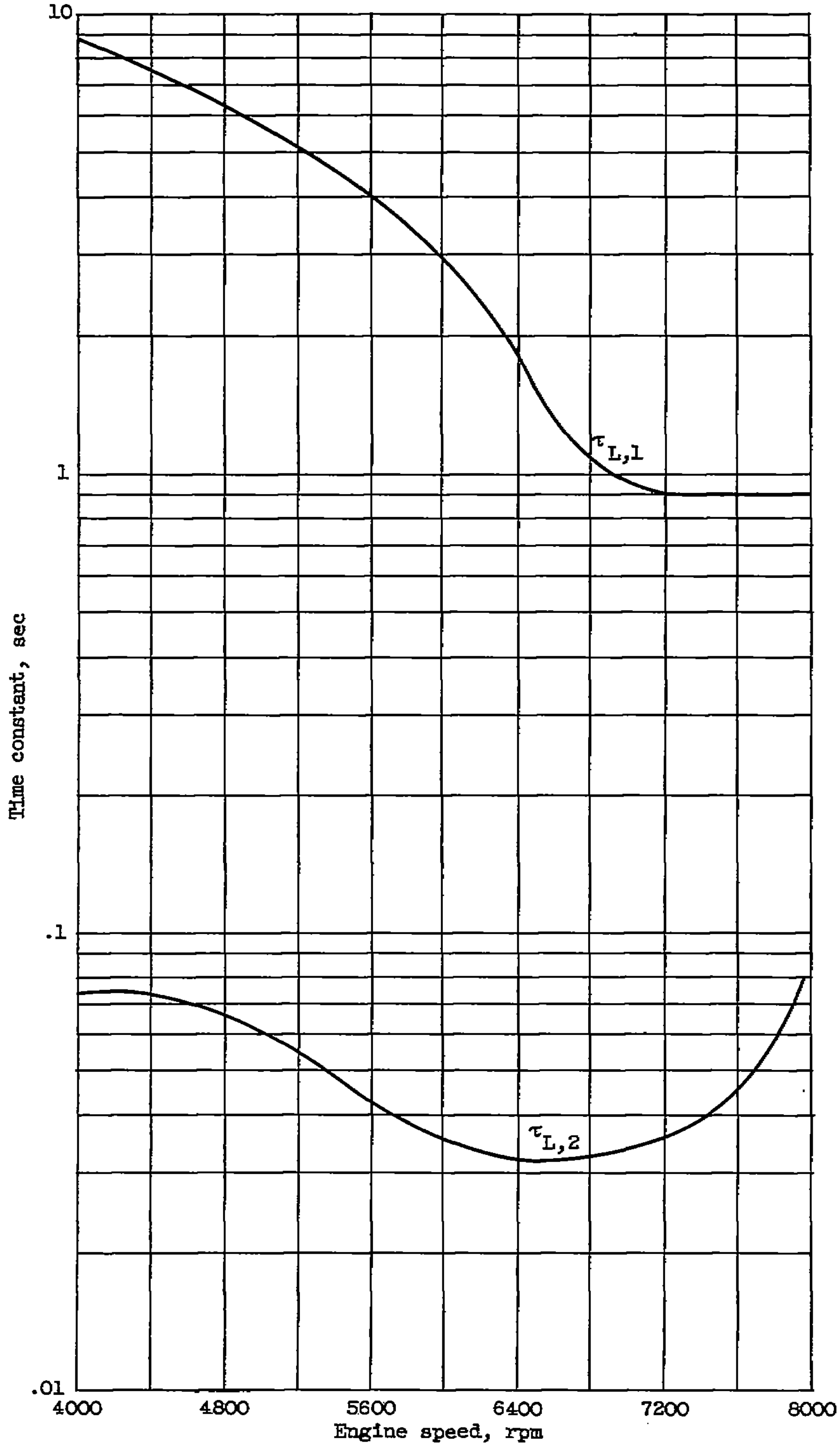

Figure 8. - Variation of engine-speed - fuel-flow time constants with speed.

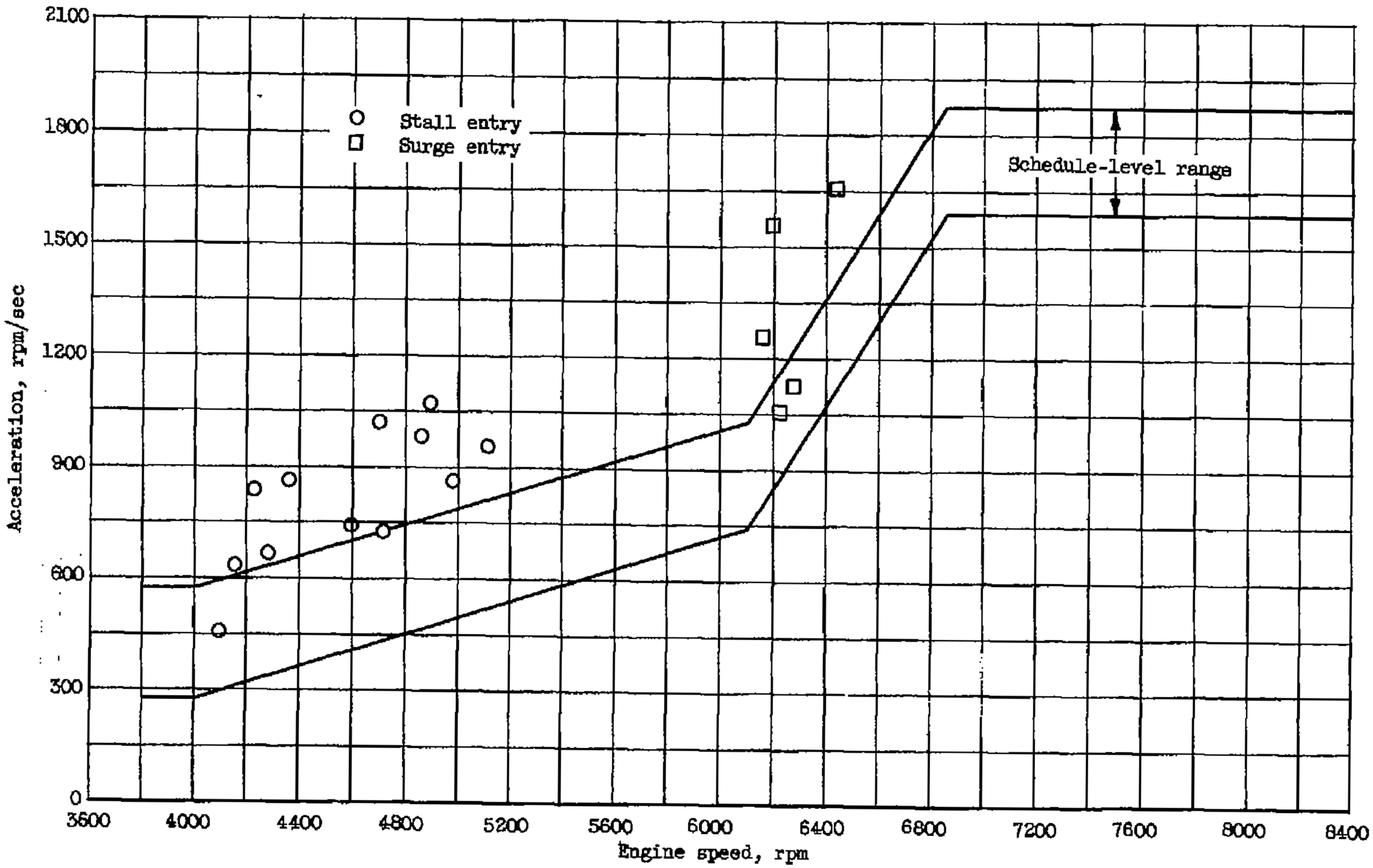

Figure 9. - Variation of stall and surge accelerations and schedule-level range used with speed.

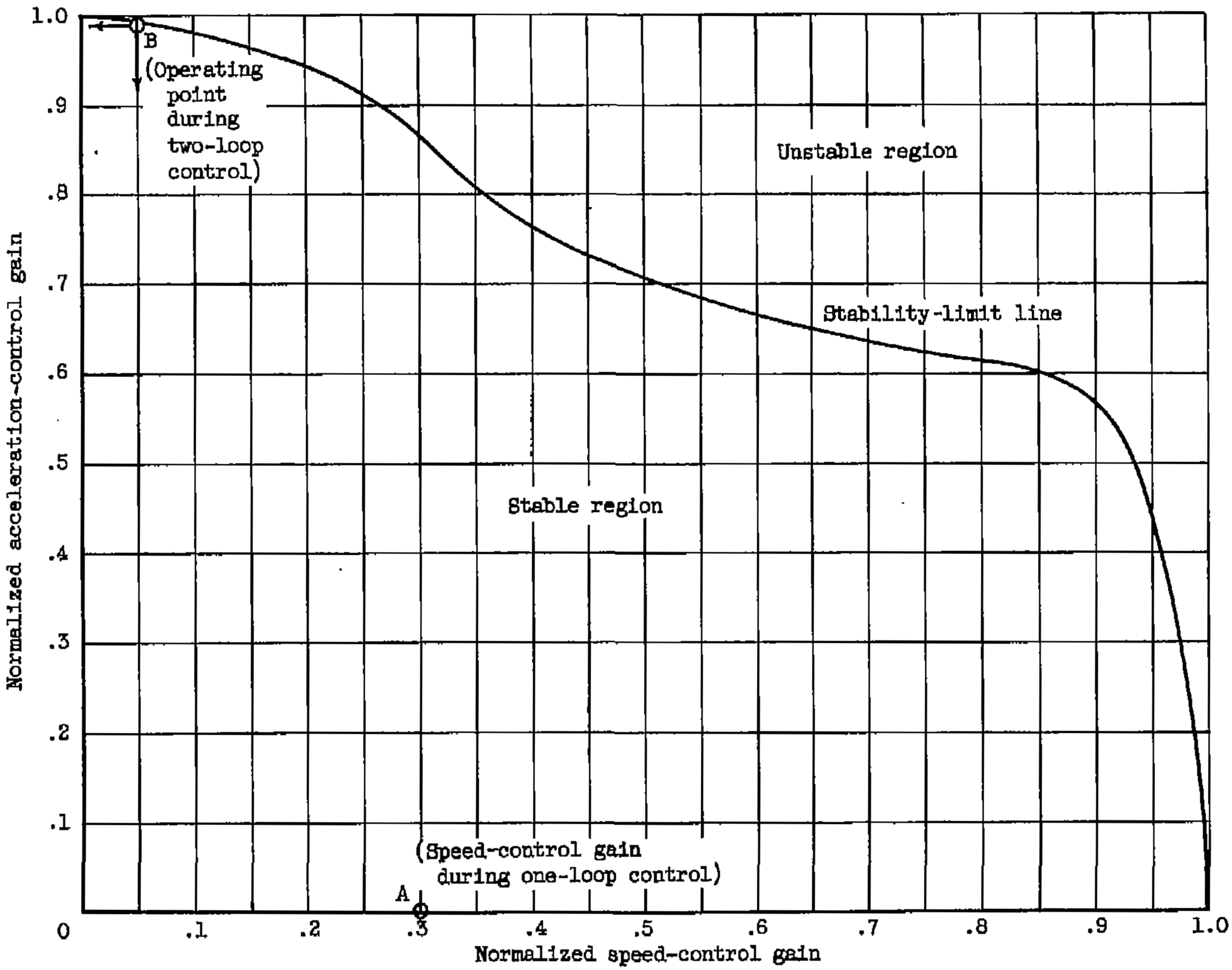

Figure 10. - Variation of acceleration loop stability-limit gain with speed loop gain (includes engine dynamics at 4500 rpm).

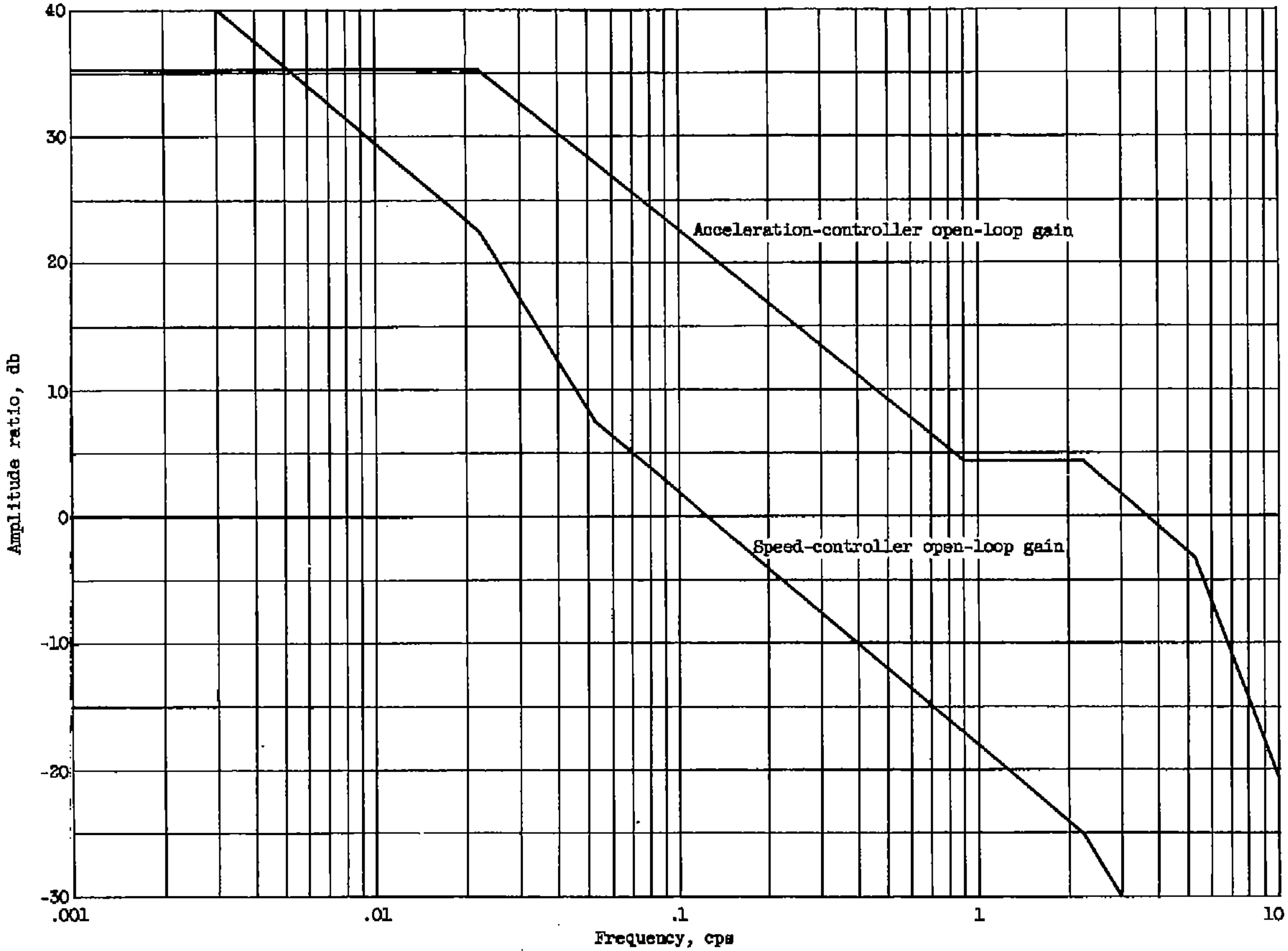

Figure 11. - Amplitude-frequency response of open-loop acceleration and speed controls at operating point chosen (straight-line approximation)(including engine dynamics at 4500 rpm).

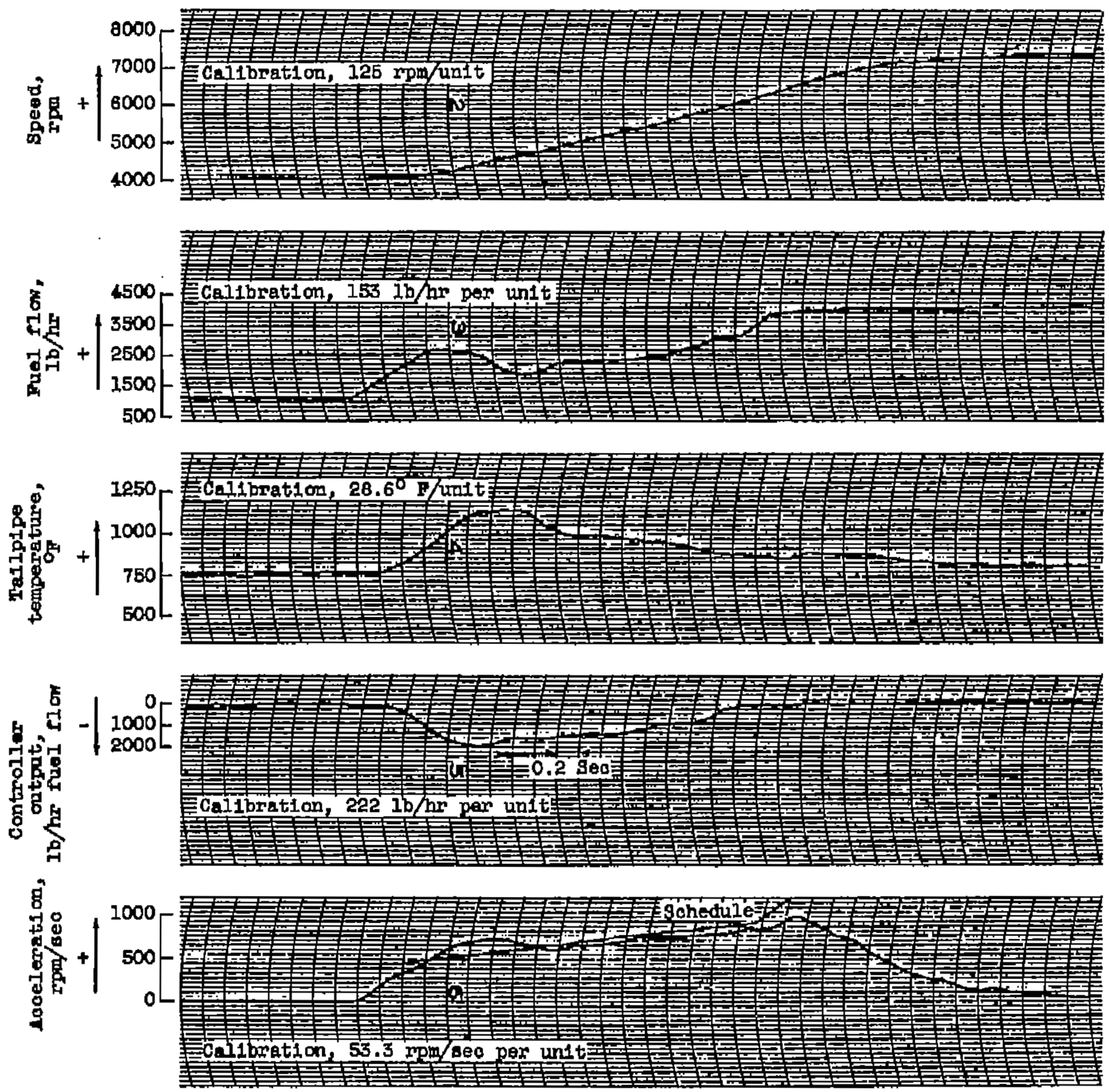

Figure 12. - Typical acceleration transient.

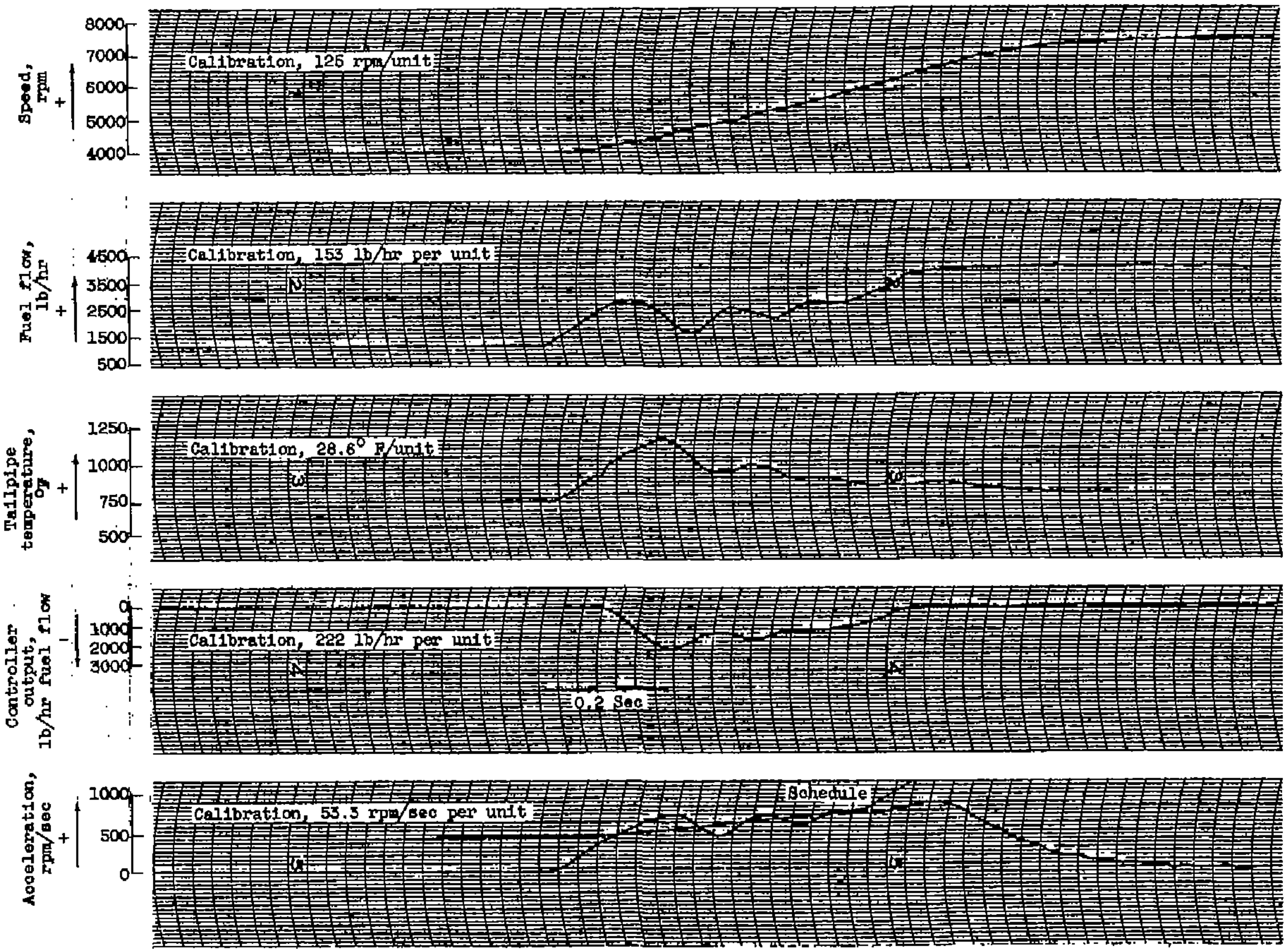

Figure 13. - Acceleration transient with instability during a part of the transient.

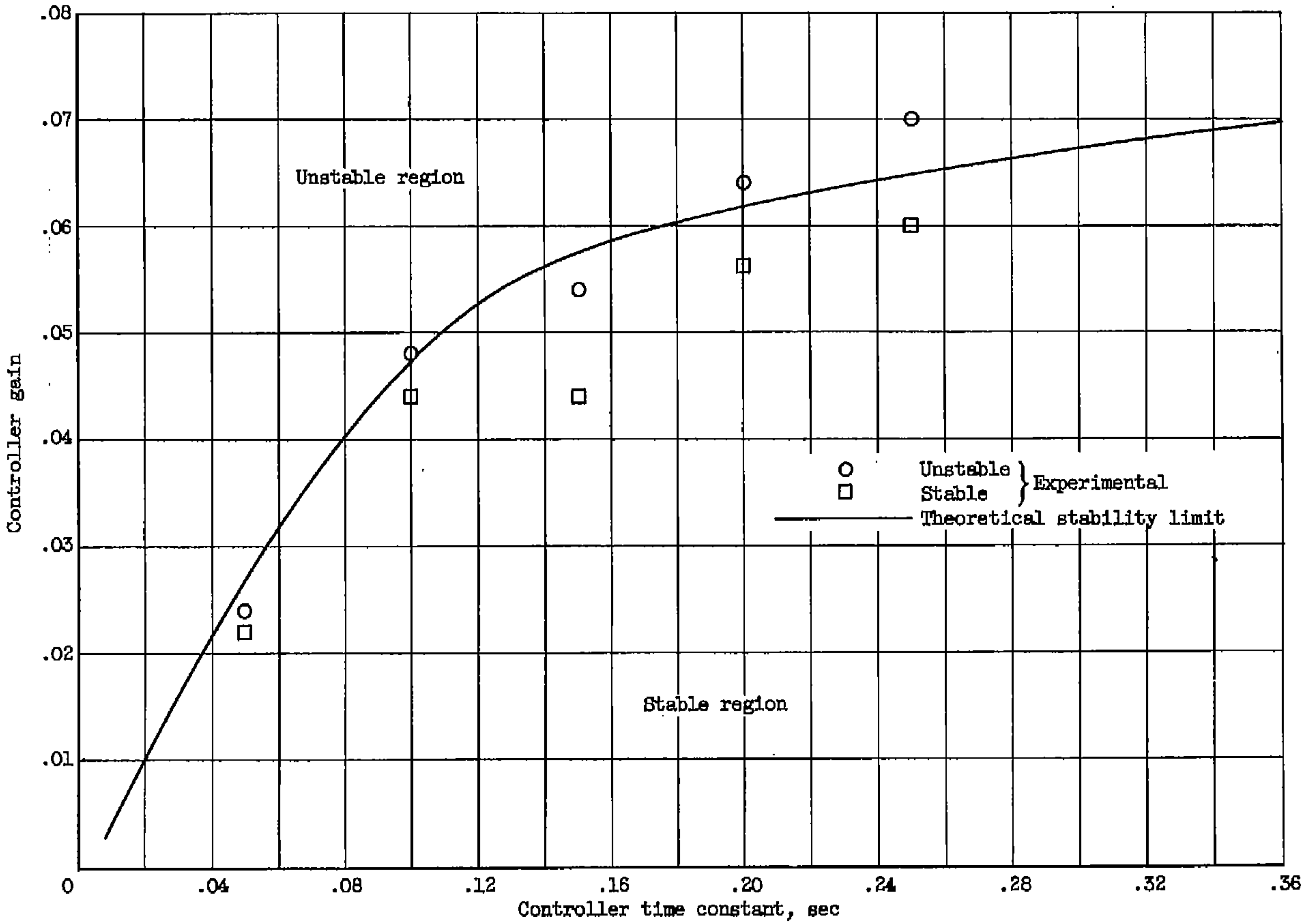

Figure 14. - Experimental- and theoretical-stability-limit gain variation with controller time constant.

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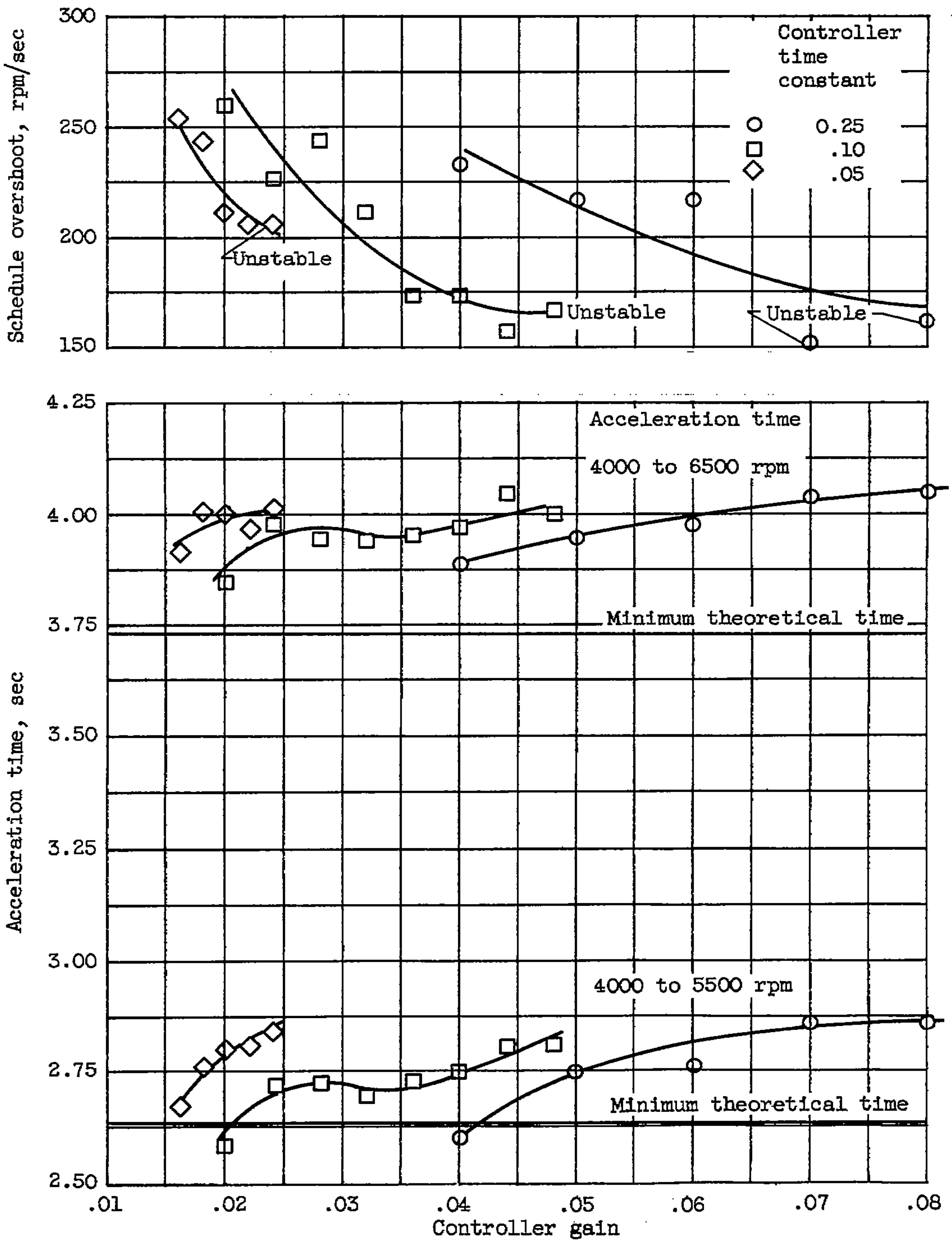

Figure 15. - Variation of schedule overshoot and acceleration time with controller gain and time constant.

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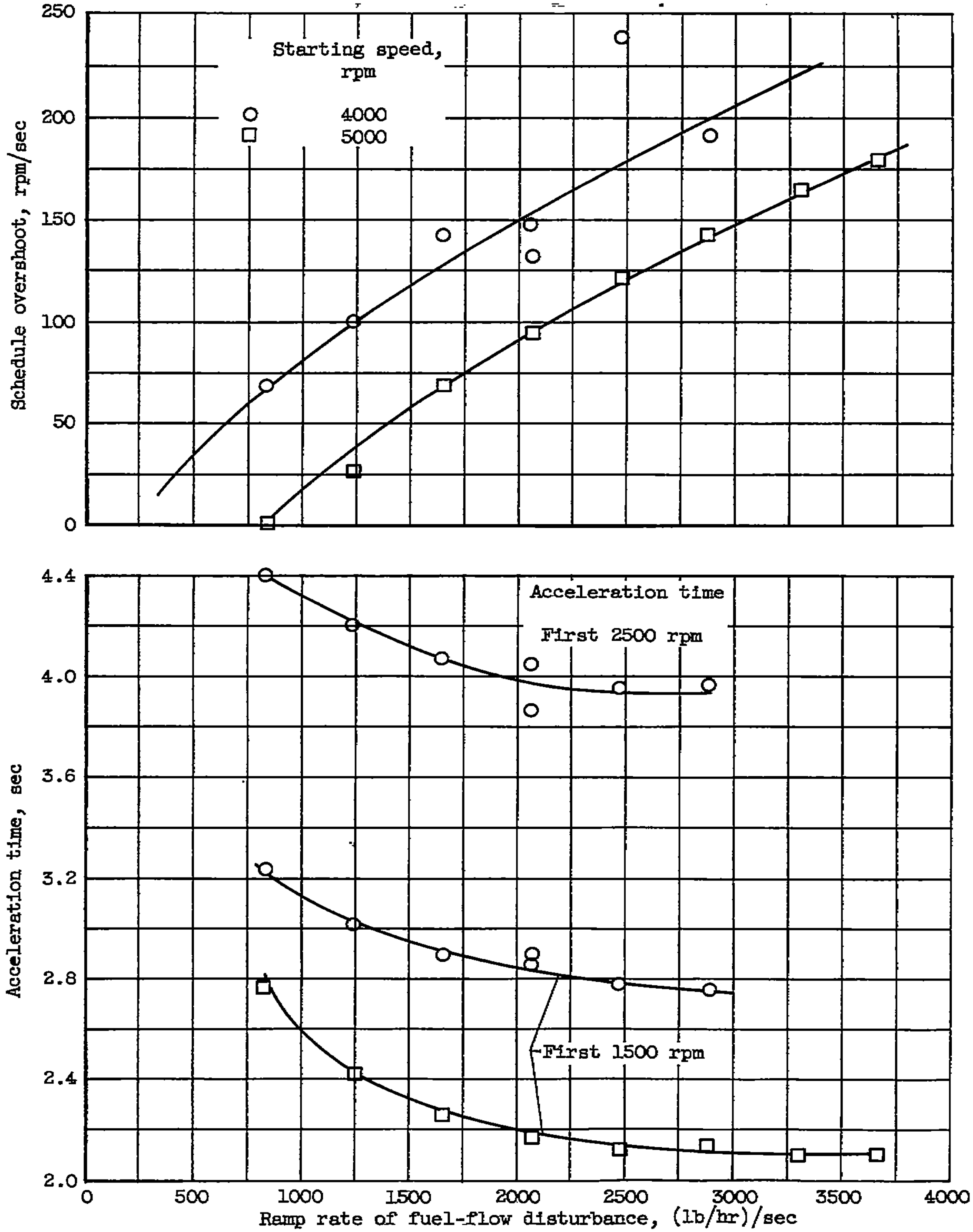

Figure 16. - Variation of schedule overshoot and acceleration time with ramp rate of fuel-flow disturbance at starting speeds of 4000 and 5000 rpm.

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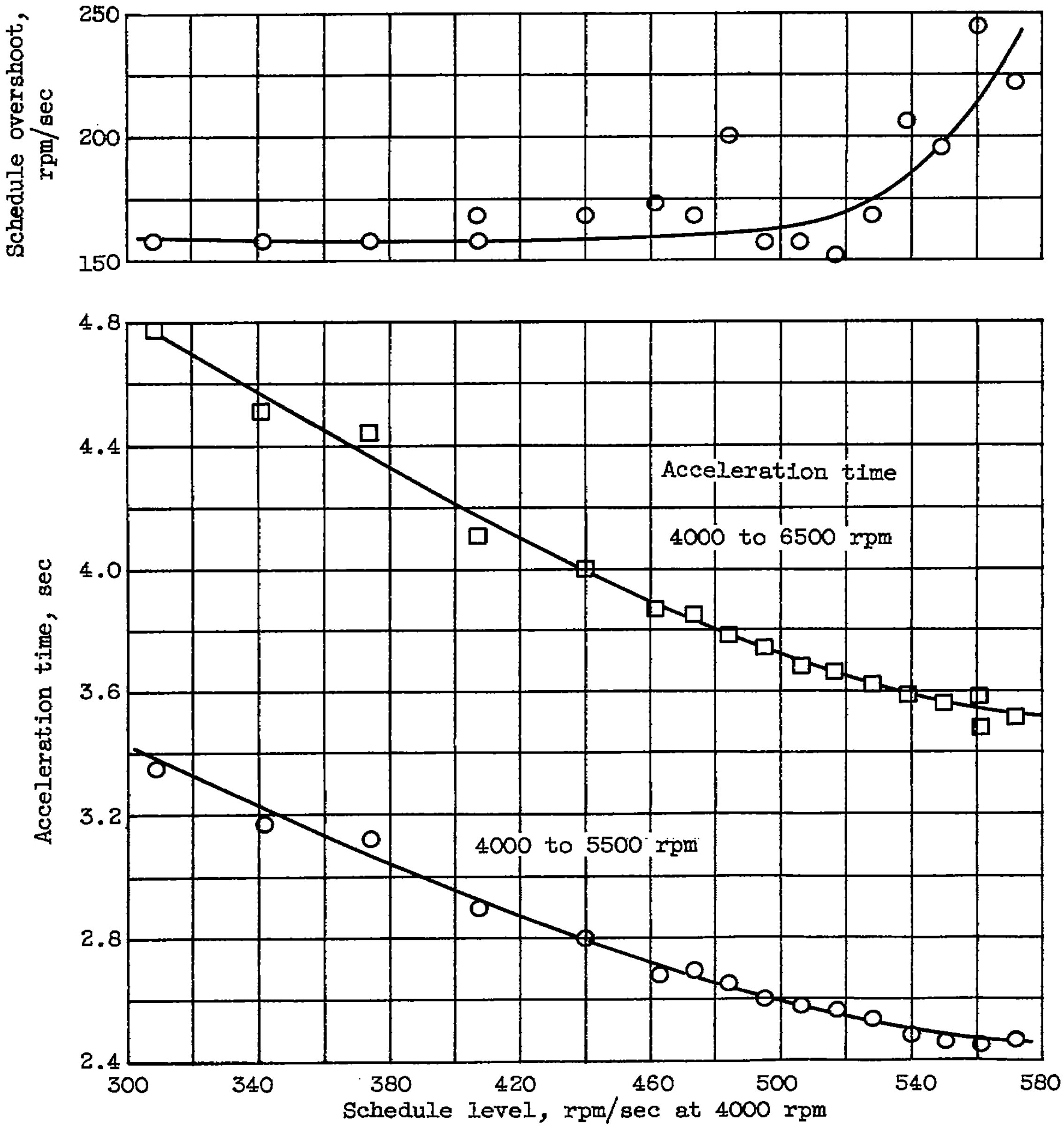

Figure 17. - Variation of schedule overshoot and acceleration time with schedule level.

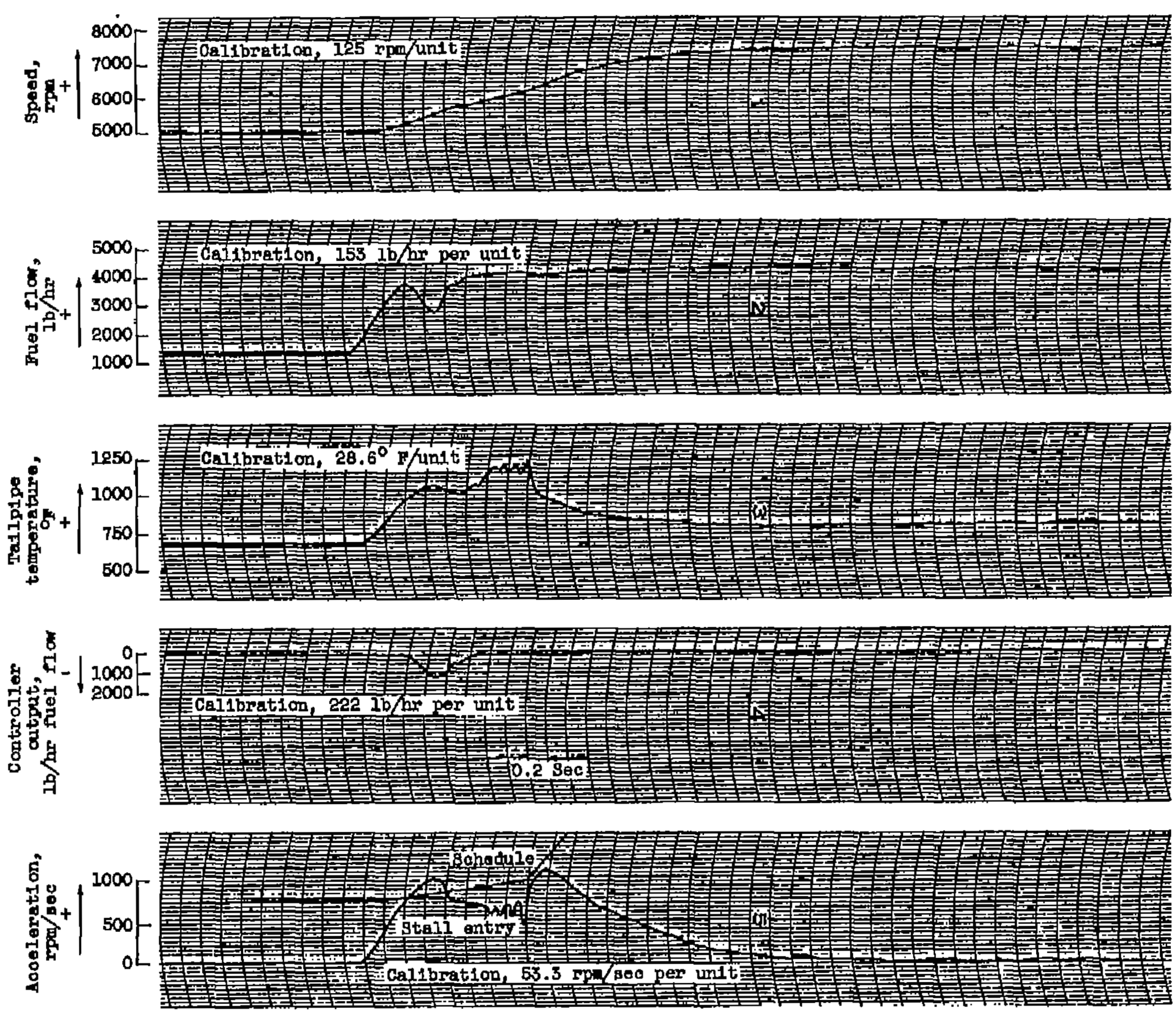

Figure 18. - Trace of acceleration transient with high schedule level resulting in engine stall.

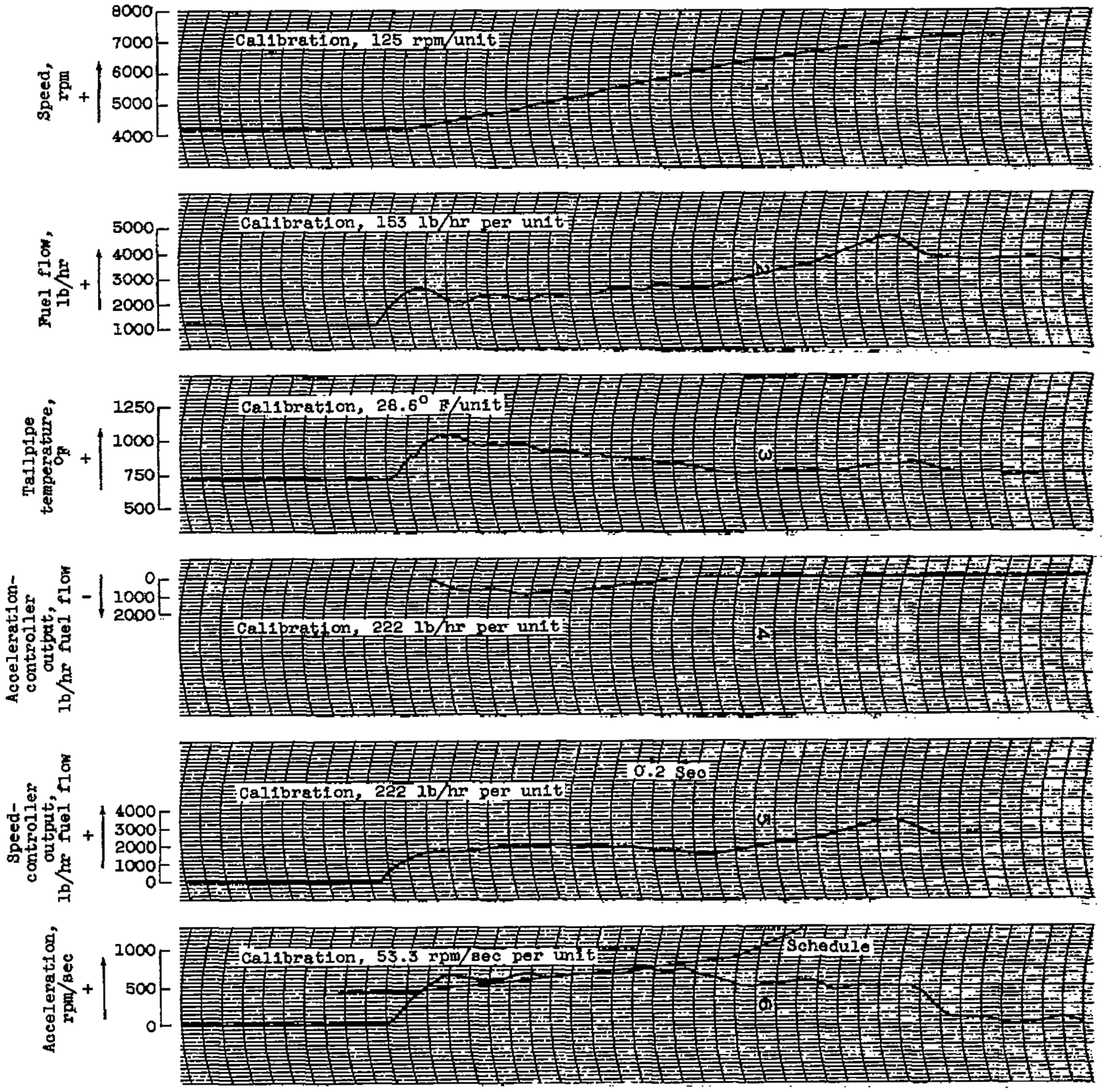

Figure 19. - Typical acceleration transient using two-loop control.

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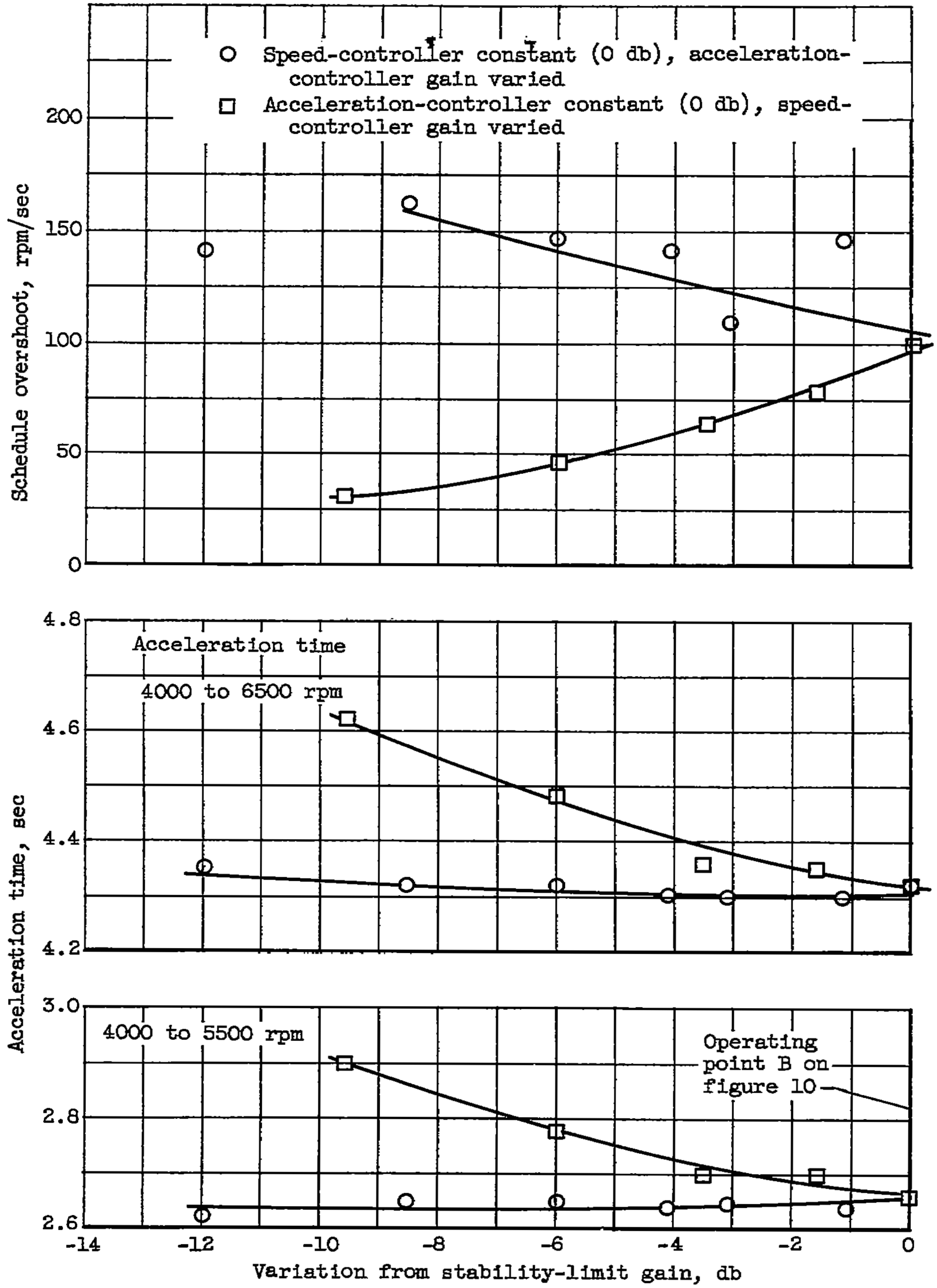

Figure 20. - Variation of acceleration time and schedule overshoot with each loop gain setting.

[redacted]

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[redacted]